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Rumford Medal Lecture

AMERICAN ACADEMY OF ARTS AND SCIENCES
1951

Adventures With Standing Light Waves

HERBERT E. IVES

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THE RUMFORD MEDAL LECTURE

The Rumford Medals are awarded by the American Academy of Arts and Sciences to the outstanding American contributors to the sciences of heat and light. This biennial premium was established in 1796 by a gift of the American-born scientist, Benjamin Thompson, Count Rumford, who won lasting fame by his contributions to the establishment of the energy theory of heat and other work in heat and light.

It has become the custom for the recipient of the Rumford Premium to present a communication to the Academy at the time he is awarded the gold and silver medals. In recent years the medalist has reviewed significant aspects of his own work. Believing that the publication of these communications would constitute a noteworthy record of American contributions to heat and light, the Academy inaugurates with this issue of its Proceedings the first of a proposed series of biennial Rumford Medal Lectures.

HARLOW SHAPLEY, *Chairman*
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THE RUMFORD MEDAL

Rumford Medal Lecture 1951

ADVENTURES WITH STANDING LIGHT WAVES

HERBERT E. IVES

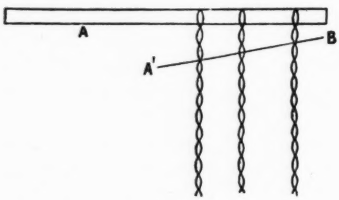
To me, the most interesting form of literature, far excelling detective stories, is scientific biography. Here one learns how the master followed up the clues, why he chose one fork of the road instead of another, why he picked one mode of investigation or instrumentation where another investigator had picked a less successful one. In this reading of scientific biography and original sources, one cannot fail to be struck by the phenomenon of *recurrence:* the scientist does not clean up the problem on the first attack, he goes back after an interval to try a different fork in the road, perhaps made more promising by other advances in the field. We find such men as Maxwell and Rayleigh going back to the same problems of color measurement after long intervals of working on other things. Another example of recurrence is shown by a scientist using the same scientific tool, in which he has become adept, to attack problems in different fields. This was impressed upon me by an early experience in the Bell Telephone Laboratories, on the occasion of an eclipse of the sun occurring in the New York Area, when a group of telephone engineers were much excited over the possibility of assembling gadgets so that they might *listen* to this gorgeous spectacle!

In casting about for a topic on which to address you tonight, I noticed that my recurrent preoccupation, either as a subject for study and experiment, or as a tool, has been the phenomenon of standing waves of light. It was the subject of my doctor's dissertation at Johns Hopkins, forty-some years ago, and I find myself still speculating on it, with the paper and pencil, which are the laboratory of a retired experimental physicist. I would like to tell you something of my adventures with these standing waves over the years.

The phenomenon of the interference of light waves, elucidated by Young and Fresnel, familiarized the scientific world with the fact that two beams of light, in constant phase relation, could be superposed to produce regions of darkness. The most extreme case of this is offered by the superposition of two beams

proceeding in the same straight line but in opposite directions. According to wave theory, whether the waves be tensional waves along a string, or waves of sound in air, or waves of light, the region above a reflecting surface should exhibit layers in continuous agitation, between which are regions of no activity. Such systems are called standing waves.

The existence of standing waves of light was not demonstrated until nearly a century after the convincing experiment of Fresnel on bright spots being formed in the middle of shadows. In 1890 Otto Wiener performed the experiment which is illustrated by Slide 1. He directed a beam of light perpendicularly upon a mirror. Above the mirror he placed an exceedingly thin photographic film, at a small angle to the surface. As the diagram shows, this film should pass through regions where the standing waves were forming nodes and loops. At the nodes there should be no photographic action, at the loops, strong action. This was in fact what he found, by the bands of photographic deposit along the developed film. Here was a demonstration of the wave nature of light, more convincing even than the classical experiments of Fresnel; for while corpuscles could be imagined as deviated into or out of a shadow, here corpuscles, if they existed, would have to be imagined as passing out of existence and being reborn, as they went to and from the mirror. Waves of course present no comparable difficulty.



SLIDE 1

The next contribution to this subject which I shall notice was actually made several years before Wiener performed his experiment. In a paper by Lord Rayleigh in 1887, on *The Maintenance of Vibrations by Forces of Double Frequency, and on the Propagation of Waves through a Medium Endowed with a Periodic Structure,* this footnote appears: "A detailed experimental examination of various cases in which a laminated structure leads to a powerful but highly selected reflection would be of value. It has occurred to me that Becquerel's reproduction of the spectrum in natural colours upon silver plates may perhaps be explicable in this manner. The various parts of the

film of subchloride of silver with which the metal is coated may be conceived to be subjected, during exposure, to *stationary* luminous waves of nearly definite wave-length, the effect of which might be to impress upon the substance a periodic structure recurring at intervals equal to half the wave-length of the light; just as a sensitive flame exposed to stationary sonorous waves is influenced at the loops but not at the nodes." (Here he gives a reference to an observation of his own eight years before.) "In this way the operation of any kind of light would be to produce just such a modification of the film as would cause it to reflect copiously that particular kind of light. I abstain at present from developing this suggestion, in the hope of soon finding an opportunity of making myself experimentally acquainted with the subject."

However, before Lord Rayleigh recurred to the subject of standing waves—he went off on another tack and discovered argon—this particular problem was taken up by Gabriel Lippmann, who actually made photographs in color along the lines of Rayleigh's suggestion and received the Nobel Prize for his work. Lippmann's procedure, in brief, was to place a photographic plate, coated with a very transparent photographic emulsion, in contact with a mirror of mercury, so that standing waves were formed in the thickness of the emulsion. When developed, the plate showed, on examination by reflected light, colors, which in the case of the bright pure colors of the spectrum, were closely those of the originally incident light. I show such a photograph of the spectrum, which, from the date recorded on it, I find I made in April 1907.

This process was my introduction to the field of standing waves. There were some things not clear about these Lippmann pictures. The reproduction of colors, while striking, was not accurate. Monochromatic radiations were reproduced as broad spectrum bands; mixed colors were a challenge poorly met; it was questioned in some quarters whether the complicated laminated structure demanded by simple theory really existed. This was long before the days of the ultraviolet microscope and of course of X-ray or electron diffraction analysis.

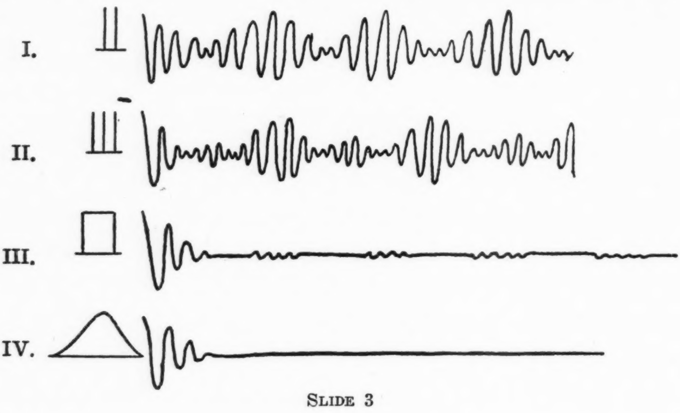
Having been brought up in an atmosphere of color photography, this was a problem that excited my interest, and I chose a study of the Lippmann process for my doctor's dissertation at Johns Hopkins. Fate played into my hands, for just at that time Ramón y Cajal reported the observation that the structure

of Lippmann films could be enlarged to observable dimensions by the simple expedient of soaking them in water, whereby they were expanded many times and brought into the range of ordinary microscopic observation.

Let me show you by a series of slides what this technique of observation brought out with regard to the actual nature of the Lippmann photographs. Slide 2 shows a section of a water-

SLIDE 2

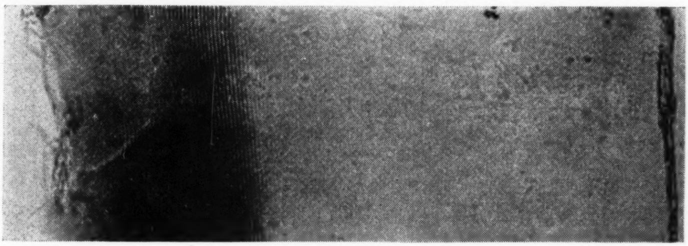
swollen section of a Lippmann film, made by exposure to monochromatic light. You will see that the layers of photographic deposit actually exist; but you will see that there are only a very few of them, close to the surface, in agreement with the observation that the reflected colors are far from pure. This point is brought out by Slide 3, which shows the calculated



SLIDE 3

standing wave systems for various monochromatic and mixed radiations. The thin layer of photographic action shown in the first photograph is obviously incapable of giving an accurate reproduction of all of these.

Some knowledge of photographic processes, acquired in a home where a photographic darkroom was considered quite as necessary as a kitchen, gave a hint to a productive line of inquiry. Lippmann plates had heretofore been developed with a very quick acting developer, namely pyrogallol, which had to be stopped in its action before the plate fogged. Now there were other developers whose action was so slow that the whole thickness of the photographic emulsion was wet before the developing action was appreciable. One such developer was hydrochinon. The next step was to develop a Lippmann plate with this reagent. Slide 4 shows a section of the resultant film.

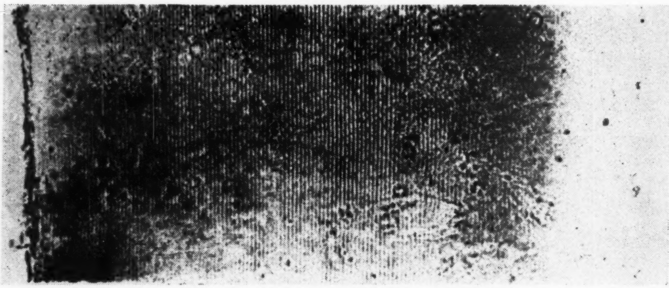


SLIDE 4

You will see that the laminations extend to a much greater depth, but cease abruptly. Why should the standing waves only exist to a certain depth? The answer to this was not far to seek. The films thus far used had been made color sensitive by the common process of bathing with sensitizing dye. It was a likely guess that it was the sensitizer, rather than the standing waves, that had penetrated only a short distance. The next step was to color sensitize by putting the dye in the emulsion before the plate was flowed. Slide 5 shows a section of such a plate after exposure to monochromatic light and development by hydrochinon. You will see that we now have laminae clear

through the film, competent to produce light by reflection of a high degree of spectral purity.

There remained one further step to be taken. While the laminae were thus proved to be present throughout the film they were useless for producing monochromatic light, because they were opaque, and only a few top laminae were effective. Here again a familiarity with photographic processes came to the rescue, in this case the observation that the first step in intensification with mercuric chloride changed a black photographic deposit into a transparent one. The plates with their

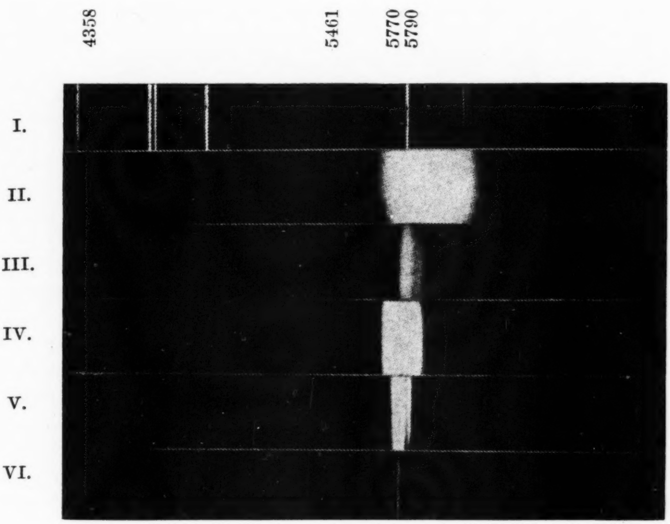


SLIDE 5

black opaque laminations were therefore treated with mercuric chloride, and there resulted laminations of alternating higher and lower refractive index, transparent to light from the whole depth of the film.

The performance of Lippmann plates so developed and so treated is shown in Slide 6, where the rendering of monochromatic radiation (the green mercury line) by films of various thicknesses is exhibited. The light reflected from the thickest film, shown at the bottom, is, in the spectrogram, hardly distinguishable from that rendered from the mercury arc directly by the spectrograph. It will be seen from these that the study was successful in clearing up the doubts which had troubled some, as to the colors being true standing wave products, and also had evolved processes for making the method approach its theoretical possibilities.

In the years immediately following this work I was occupied with problems of photometry and illumination. That was a heroic period in photometry, with new, more efficient light sources being rapidly developed, with a host of problems connected with their varying colors, and the need for correlating photometry with the newly formulated laws of radiation. Illustrative of my introductory remarks, I found a use for standing waves in one of the photometric problems. One of the older suggestions for comparing lights of different colors was what was known as the Crova method. This consisted in making the observation by monochromatic light. It suffered from

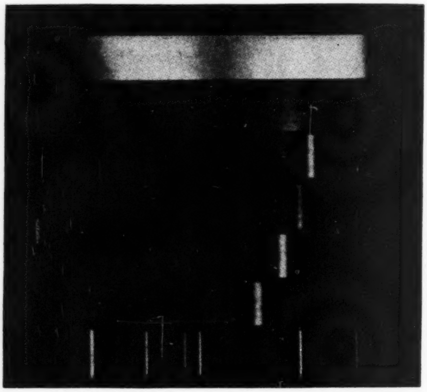


SLIDE 6

the disadvantage that one must use a spectroscope to get the monochromatic light, and that the exact wave-length to be used had to be slightly varied according to the emission characteristics of various sources. Now these special Lippmann plates offered a simple means for observing by monochromatic light, and they had the peculiarly apt characteristic of shifting

the wave-length of the reflected light by a slight change of the angle at which they were observed, — they were "light sirens". In Slide 7 I show a spectrogram, made to illustrate these properties, in which you see how a highly monochromatic reflection is shifted along the spectrum by rotation of the plate. This method of photometry was not destined to have wide use, because the newer illuminants presented too much diversity of radiating characteristics for the Crova method to be valid. I tell you about it merely to illustrate how an investigator recurs to tools with which he is familiar.

All work along these lines was interrupted when we entered the war in 1917, and I found myself in the Army Air Service,



SLIDE 7

working on apparatus and methods for aerial photography. The technical problems were sufficiently engrossing, but hardly less difficult was that of convincing the military mind of the value of photographic reconnaissance. According to Sir Douglas Haig, "reconnaissance always has been and always will be made by cavalry". Now cavalry has disappeared, and millions of aerial photographs were made in the last war, by apparatus and methods many of which had their inception in our Langley Field laboratory.

Following the war I went to the Bell Telephone Laboratories. When asked what I would choose to work on I said "the photoelectric effect" with which I had become enamored as a tool for photometry. I was gently but firmly told that no use was foreseen for the photoelectric effect, and instead I was to work on a very pressing problem, namely electrical contacts. This I did for several years, with results of some value in connection with the reliability of the telephone, but of no interest to the Rumford Medal Committee. I did use optical methods at times in the study of contact operation, but not standing waves.

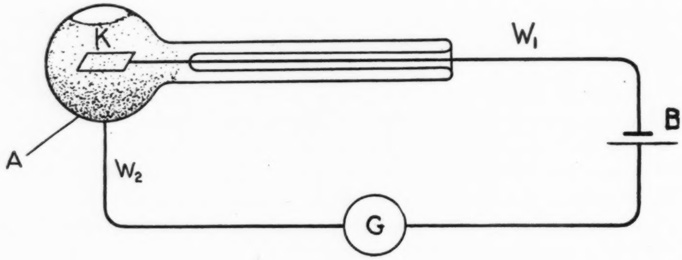
I must confess that while working on electrical contacts I was insubordinate to the extent of doing a little work on the side with photoelectricity. This did not prove to be such a bad thing, because it gave me confidence to urge that the problem of transmitting pictures over telephone lines be seriously studied. The outcome of this was the picture transmitting system which has now become nationwide and so commonplace as to be taken for granted. Thirty years ago, as some of you will remember, when I point it out, newspaper pictures of distant events appeared only days afterward. Now it is usual for the majority of newspaper illustrations to come in by wire, as quickly from San Francisco as from Cambridge.

As a sequel to the transmission of photographs came the first complete realization of television, with the transmission of moving images beyond the limits set by the curvature of the earth. This development, a combination of the photoelectric cell, tracing back to Hertz and Elster and Geitel, with the audion of DeForest, has gone far since 1927 when in New York we talked with and saw people in Washington; and the end is not yet in sight.

We seem to have wandered rather far from the subject of standing waves, but they are to come up again. After this intensive period of application to the problem of putting vision into the communication art, when I again raised the question of studying the photoelectric effect, there was no voice raised to protest that it was an unpromising field. It was in the studies then started that I found myself once again playing with standing light waves.

These studies were aimed at elucidating certain problems in the nature of the photoelectric effect; finding "the go of it" as Maxwell put it. Why are photoelectrons more copiously emitted at certain wave-lengths than others; why is the emis-

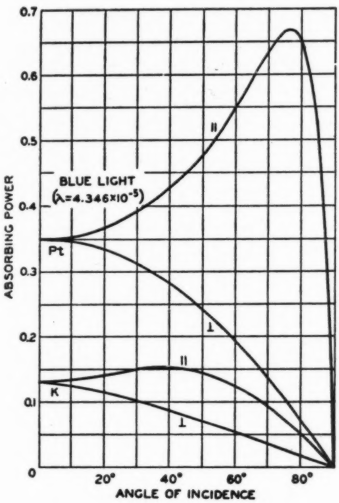
sion enormously affected by the state of polarization of the exciting light? In order to make clear what these problems were, let us look at a schematic photoelectric cell of the type in which these phenomena are most strikingly exhibited. In Slide 8 we have depicted a glass bulb, in the center of which is a flat highly polished metal plate, say of platinum. The inside of the bulb is given a conducting metallic coating, with a window through which light may enter. This coating, and the central plate, are both connected, by wires through the glass, with an external closed circuit, furnished with current measuring instruments. Into the bulb is introduced a small quantity of an alkali metal such as potassium. The bulb is exhausted to a



SLIDE 8

high vacuum, the metal plate is raised to a high temperature by thermionic bombardment, to clean it, and the alkali metal allowed to build up, by its vapor pressure, an extremely thin stable film, only a few atoms thick, so that the metal plate becomes a photosensitive cathode.

Let us consider first what happens when the light falling on the cathode is polarized. It has long been known that at high angles of incidence the emission is greater for light polarized with the electric vector cutting into the surface. This was in agreement with the fact that the absorption of light is then greater, but the puzzling fact was encountered that this difference in emission for the two planes of polarization, which could only amount to a factor of two or three to one, on the basis of the absorption, actually amounted in the case of these thin films to ten or more. This is illustrated by the next slides,



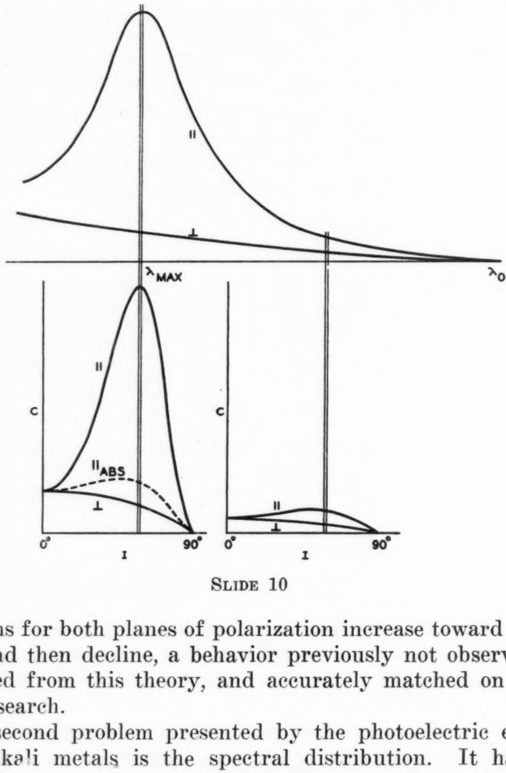
SLIDE 9

where we have first in Slide 9 the absorption of light for platinum and potassium at different angles of incidence, for the two planes of polarization (denoted by || and $\perp$), showing a maximum difference at 60 degrees incidence represented by a factor of about two; and in Slide 10 (lower left diagram) the photoelectric emission from a thin film of potassium on platinum for the same conditions of illumination; here we see the ratio of emissions at 60 degrees amounting to nearly ten times.

The clue to this phenomenon is found when we recognize that above the metal mirror there exists a system of *standing waves.* The film of potassium, of thickness only a small fraction of a wave-length, lies just above the mirror surface; the light energy active in it will be that of the standing wave system at that point. This can be calculated from the refractive index and extinction coefficient of the metal base. In Slide 11 we see these calculated standing waves from the surface outward for two representative metals, silver and platinum, for the two planes of polarization, for light incident at various angles from zero to 80 degrees. You will note that while for normal incidence the standing waves for both planes of polarization exhibit a node at the surface, at higher angles of incidence the plane for which the electric vector cuts into the surface approaches a loop. The consequence of this is clearly shown in Slide 12, where the computed intensity curves, at various angles of incidence, are shown (full lines) for the two planes, || and $\perp$.

You will see that the crucial point — the enormous ratio of the photoelectric emission for the two planes of polarization at high angles of incidence — is completely accounted for by this theory that the emission is proportional to the energy density in the standing wave system set up over the supporting metal

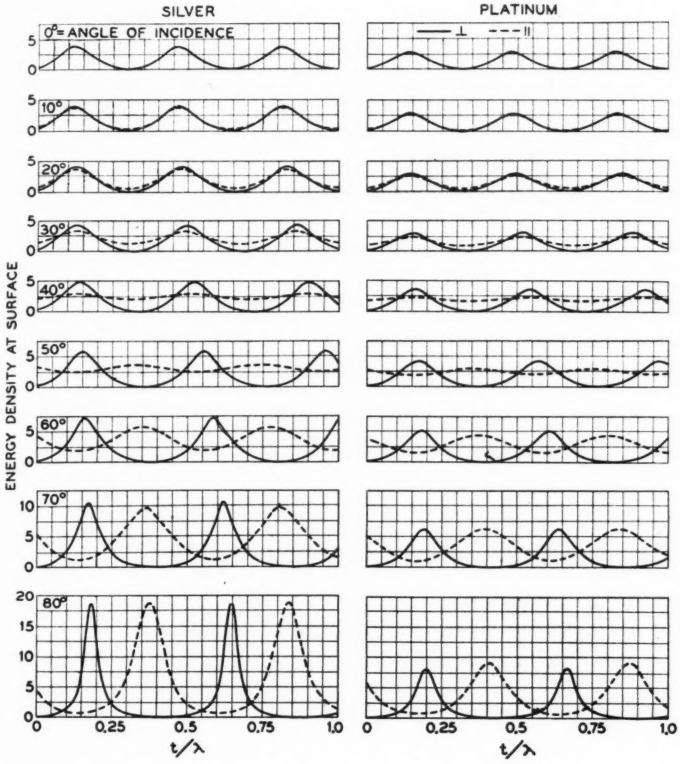
surface. The success of the theory even to small details is shown by Slide 13, where the photoelectric emission of a thin film of rubidium on glass is shown, as computed (full line) and as measured (dots and crosses). Notice that in this case the



SLIDE 10

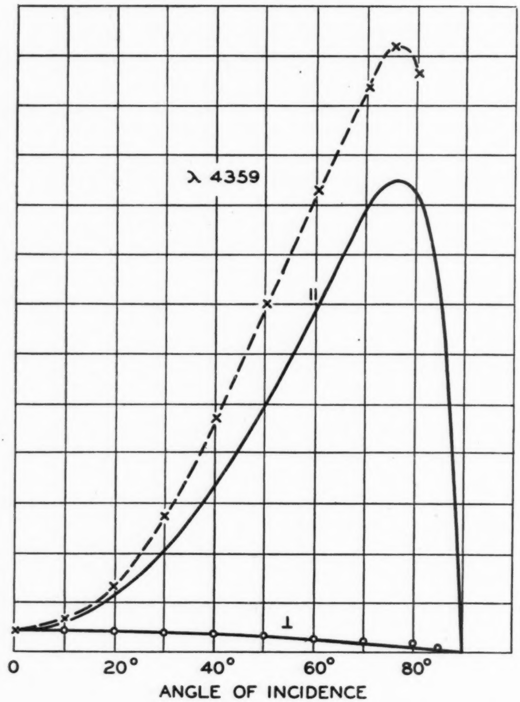
emissions for both planes of polarization increase toward a maximum and then decline, a behavior previously not observed, but predicted from this theory, and accurately matched on experimental search.

The second problem presented by the photoelectric emission from alkali metals is the spectral distribution. It has been known for a long time that the maxima of emission move progressively toward the red with increasing atomic weight, as shown by Slide 14. The reason for this was completely vague; some attempts had been made to correlate the maxima of emission with the size of electronic orbits. No relationship with the optical properties of the materials had been explored, partly due to the fact that the optical properties of the alkali metals were imperfectly known.



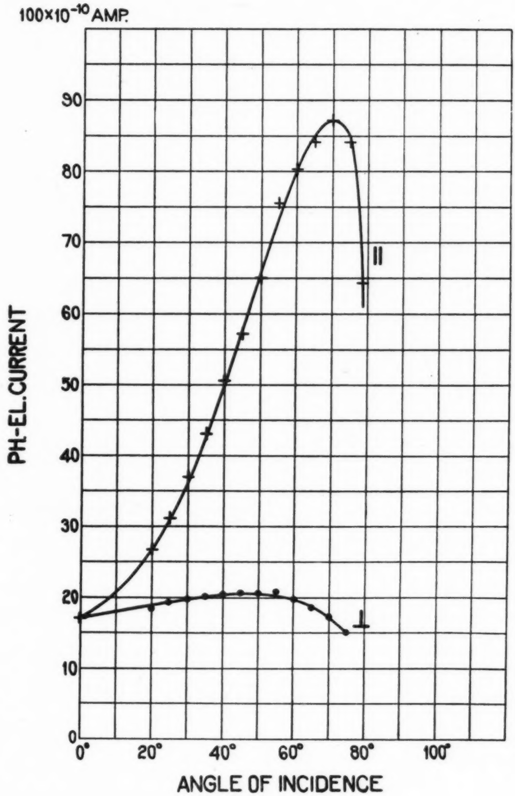
SLIDE 11

The same line of attack which you have seen lead to the elucidation of the vectorial and polarization phenomena has led to a very complete understanding of the spectral emission characteristics of thin photoelectric films. The picture to which we are led is that the thin film at the foot of the standing wave system absorbs light according to the intensity of the standing wave, and in proportion to the optical absorption of the alkali metal; the photoelectric emission is proportional to this absorption. This picture requires for its test a knowledge of the



SLIDE 12

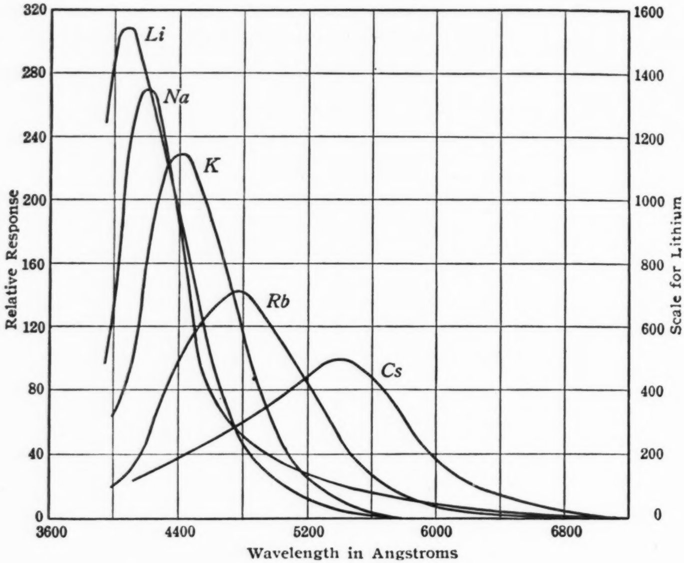
optical constants—the refractive index N, and the extinction coefficient K—of the alkali metals. The determination of these constants presented an experimental problem of considerable difficulty, for the metals must be measured in vacuo and must be prepared so as to have specular surfaces. This investigation of the optical properties of these metals, which is a story in itself, gave a set of data, represented by Slide 15, in which you will see a set of similar N and K curves, moving toward the red, as we go from sodium to cesium. With these curves available, straight application of the theory gave a set of curves of computed photoelectric emission, when calculations were made for a plausible thickness of the sensitive layer, which are shown



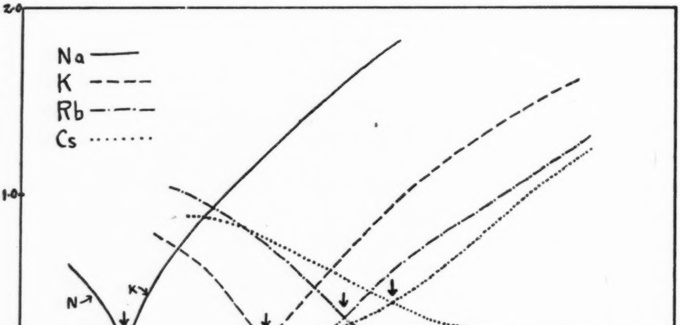
SLIDE 13

in Slide 16. You will note that the progression of maxima toward the red is clearly predicted. The maxima in fact lie at the crossing points of the N and K curves.

When these predictions are compared with experiment, as shown in Slide 17, it appears the true distributions of emission (shown by the solid lines) are somewhat shifted toward the violet, and are less pronounced. This discrepancy is however entirely explainable if we assume, not one and the same thickness

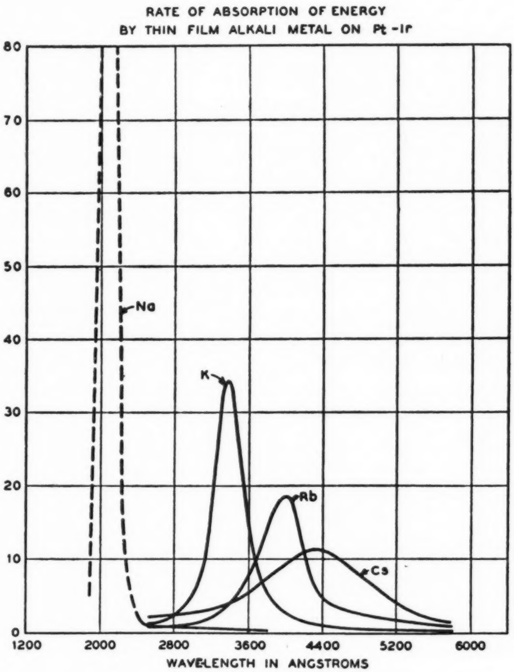


SLIDE 14



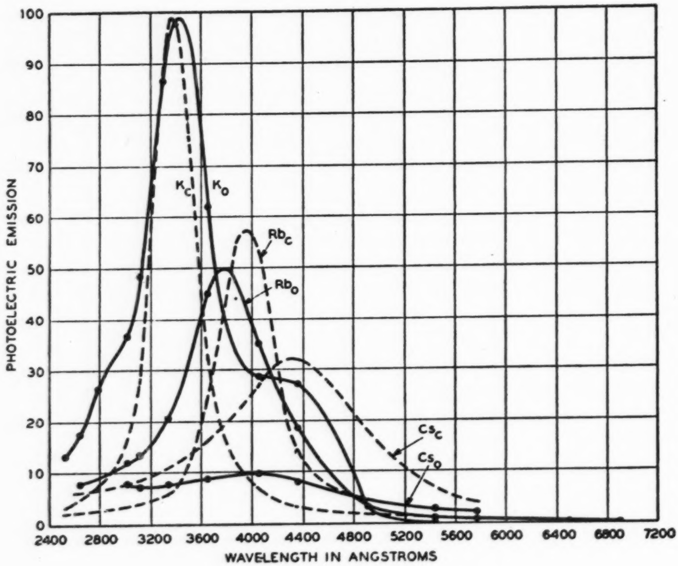
SLIDE 15

for the thin spontaneously evaporated films, but different thicknesses for the different metals. How closely the fit can be made between calculated and experimental emissions is shown in the next two slides. Slide 18 shows (dashed line) the computed and (full line) the observed emission for rubidium; Slide 19 the same data for cesium.

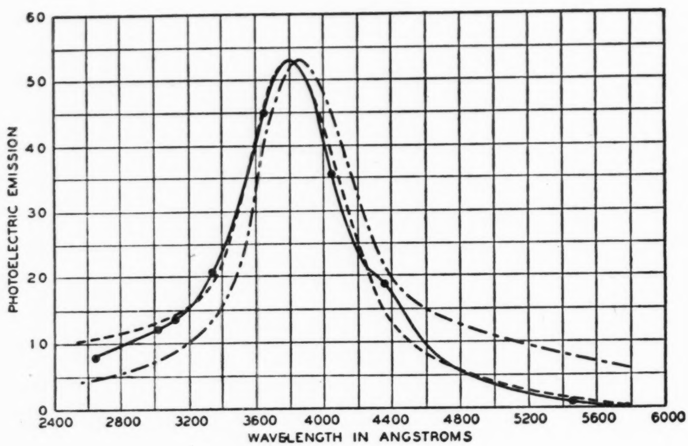


SLIDE 16

The significance of these experiments, which I wish to impress upon you, is that it is the *optical* properties of the materials, and the optical conditions of the region in which the phenomena occur, which explain these outstanding effects. I stress this because other attempts at explanation, which have



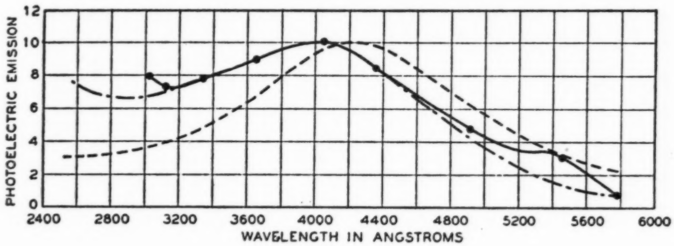
SLIDE 17



SLIDE 18

been made from quantum mechanical considerations, have almost uniformly neglected or ignored the optical factors. These, instead of being secondary or negligible, really dominate.

The last experimental adventure with standing waves of light which I want to discuss brings us full circle. It is a repetition

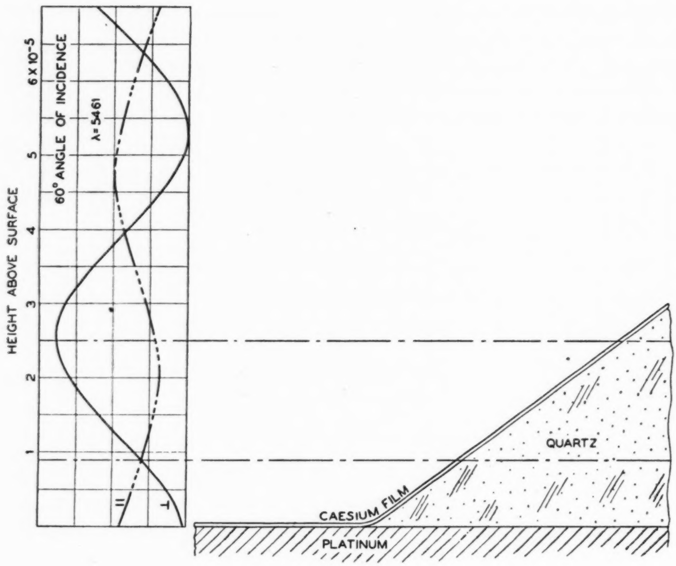


SLIDE 19

of the experiment of Wiener, with which I introduced the subject, but with this difference, that instead of the thin photographic film which Wiener used, a thin photoelectric film was employed. The scheme of the experiment is shown in Slide 20. A quartz wedge was built up on platinum, by evaporation from a quartz-coated tungsten wire. On the platinum and quartz a thin film of cesium was allowed to form. You will see that by this means the standing wave system which thus far we have examined photoelectrically only close to the reflecting surface can be similarly examined for a series of positions above that surface.

At the left of the slide is a set of computed curves showing the intensities for the two planes of polarization, for light incident at 60 degrees, at different distances above the platinum. It is evident that we may expect a variety of relations between the emissions at different positions along the wedge and for different polarizations of the incident light. What is here given for one angle of illumination is repeated with variations for other angles, leading to complicated relations, all however susceptible to exact computation.

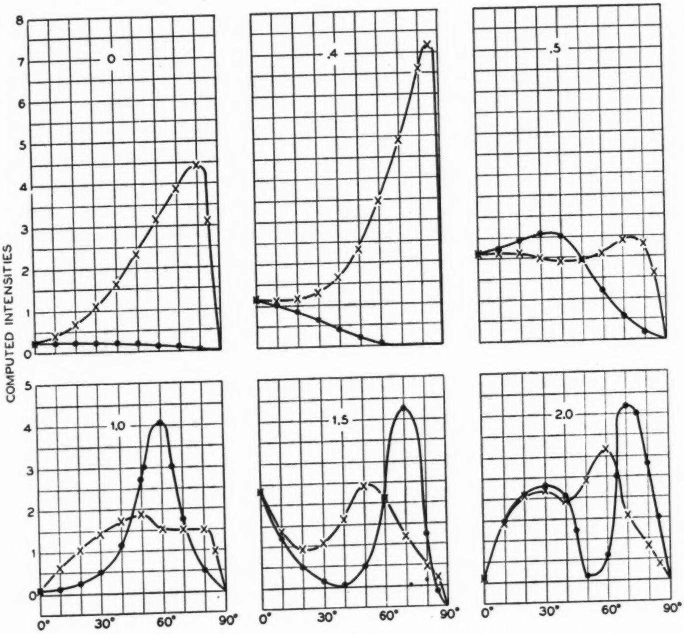
In more detail, we see in Slide 21 what we are led to expect, by computation, for a number of different thicknesses of the wedge, through the complete range of angles of incidence. These relations are most involved, and behaviors are predicted



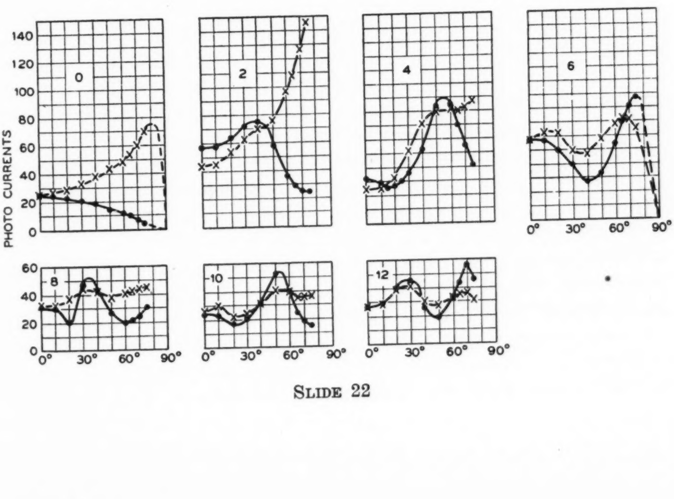
SLIDE 20

never seen before by land or sea. Instead of the simple falling off of emission with angle, or the simple rise to and decline from a maximum, we have actually multiple maxima, with the emissions for the two planes of polarization reversing their positions. On exploring the quartz wedge with a small spot of light, and measuring the photoelectric emissions, we do in fact find all of these predictions borne out, as is shown by Slide 22. The verification of the electromagnetic wave theory of light furnished by this experiment considerably transcends, I think, the original simple experiment of Wiener, conclusive as that was quite properly considered.

I shall devote the remainder of this address, not to experimental adventures with standing waves, but to adventures in the contemplation of these phenomena — to speculations on their significance in the realm of theory. What do they contribute to the old question of the nature of light, to the recurrent question of waves versus corpuscles?



SLIDE 21



SLIDE 22

The last experiment showed how minutely the photoelectric emission followed the predictions made from the wave nature of light. Yet it is from this very photoelectric effect that the wave theory has received its most serious challenge. Philip Lenard, over fifty years ago, in studying the photoelectric effect, found that the energies of the ejected electrons were quite independent of the intensity of the exciting light. Einstein, in 1905, proposed that the energies associated with the photoelectrons be identified with the quantum of energy discovered by Planck, proportional to the frequency of the light. This identification has been abundantly confirmed, notably by the experiments of Millikan. In addition to the idea that a photoelectron carries the energy $h\nu$ Einstein also proposed, as a "heuristic" view, that this amount of energy was also discrete in the radiation before it encountered the electron. This is equivalent to the assumption that light travels in bundles — now called "photons". This is a return to the corpuscular theory toward which Newton is commonly represented as having inclined. It is this photon conception of light which has of late attracted most attention.

But however attractive from some standpoints the photon appears, it has not been acceptable to those of wide acquaintance with the intricate phenomena of optics. The case was well stated by H. A. Lorentz in an address in 1910, from which I quote the following extract: "Nevertheless the speaker holds the hypothesis of light quanta to be impossible, if the quanta are regarded as wholly incoherent, an assumption which is most natural and which is also made by Planck. The impossibility of incoherent quanta follows from a consideration of interference phenomena. Specifically Lummer and Gehrke have observed interference at a phase difference of two million wavelengths; for yellow light, that corresponds to a length of one meter. If each quantum by itself should be capable of giving sharp interference, then it must also itself extend over that length in the direction of propagation. But, the lateral area of the quantum must also be considerable, which follows from the diffraction theory of optical instruments. Should a light quantum cover only one square centimeter of area, then it would be obviously senseless to fabricate large telescope objectives, for only a small fraction of the area would be used by each quantum in the production of images; on the other hand it is well known that the clearness of images can be greatly en-

hanced by large objectives. Thus a light quantum would have to be as large as the largest telescope objectives, and, since it is unlikely that the volume of the quantum adjusts itself to our instruments, it would be necessary to conceive of it as considerably larger. But then, only fractions of quanta could get through a small opening such as the pupil of the eye. According to the hypothesis of absorption by the retina, only whole quanta can be taken up, so that fractions would have to recombine into whole quanta. Moreover, the consideration of the simplest interference phenomena, such as Newton's rings, shows that the quanta must be divisible, because in the process the ray is resolved by reflection into two parts which travel by different paths and finally come to interference.''

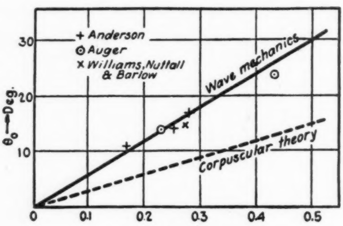
To this expression of dissent is to be added that of Henri Poincaré, who in his only published reference to Einstein remarks that while Einstein would put the quantum in the incident light, he, Poincaré, would place it in the molecule; and he speaks elsewhere of finding the ''vestibule'' by which the molecule admits or releases energy in quanta.

Now the objections raised by Lorentz, that the phenomena of interference are incompatible with the idea of photons, are encountered in their extreme form, one might say ''head on'', in the phenomena of standing waves. If light consists of streams of photons, then in their reflection at a mirror, if they are incoherent, they must alternately exist and not exist, in the loops and nodes. This is a much harder thing to swallow than the fits of easy and difficult reflection suggested by Newton. If, on the other hand, each photon has a structure adequate to account for interference, it must be a most complex one to account for the existence of polarization and directional effects. This structure would have to be of atomic dimensions to fit the experiments described above. But we must also include in our survey standing waves of all dimensions, among which are mile-long radio standing waves, which would mean that the photons in such radiation must also be miles long. The objections to photons which Lorentz cited in terms of the pupil of the eye and the aperture of astronomical telescopes must, when we consider standing waves, be extended to atomic dimensions at one end and intercity distances at the other. The concept of photons becomes fantastic.

Refuge has been taken from this unsatisfactory state of affairs by using wave descriptions for some phenomena and photon

descriptions for others, and it has been claimed that the two types of phenomena are never met in the same experiment. I submit that the last experiment described, the repetition of Wiener's experiment, certainly comes very close to showing both types of phenomena in conjunction. Electrons are emitted with energy $h\nu$, but they follow minutely the orders of the standing wave pattern.

Now the way out of this unsatisfactory situation is I believe furnished by one of the most important developments of physical theory in our time; I refer to the wave mechanics of de Broglie and Schrödinger. This wave mechanics may be looked upon as the happy hunting ground of the student of standing waves. An element of matter according to it *is* a standing wave system. It is not however on the standing wave aspects of wave mechanics that I wish to dwell. It is rather to this fact: that wave mechanics puts the h of quantum theory in the *atom* and not in the *radiation*. It provides in short that "vestibule" that Poincaré demanded, in order to avoid the unacceptable idea of photons.



SLIDE 23

Wave mechanics has rather triumphantly done this when used to develop the theory of photoelectric action, in the hands of Beck and Sommerfeld. Carrying the theory into the region of X rays, they have shown that the distribution in direction of ejected photoelectrons differs significantly when light is considered as waves or as particles. This is illustrated by Slide 23, which shows how the "bi-partition angle" differs by a factor of two for the two cases, and that the experimental results are decisive in favor of the wave mechanical picture as against the corpuscular.

In fairness to Sommerfeld I should say that he expressed his preference for the corpuscular interpretation as furnishing a more "causal" explanation than does the wave mechanical. Now why with the facts before him he should cling to a concept which they refute is a problem for the psychologist rather than the physicist. With the background of a student of the interference of light, particularly of standing waves, the more appropriate conclusion would appear to be the sentence with which Lorentz concluded the address to which I have referred above, "von Lichtquanten, keine Rede sein kann"—"photons just won't do".

Count Rumford, in his epoch-making communication to the Royal Society of 1798, on the heat produced by friction, posed the question: "What is Heat? Is there any such thing as an *igneous fluid?* Is there any thing that can with propriety be called *caloric?*", and concluded, "it appears to me to be extremely difficult, if not quite impossible, to form any distinct idea of any thing, capable of being excited and communicated, in the manner Heat was excited and communicated in these experiments, except it be MOTION".

It appears to me that we are faced in optics with the same kind of question which Rumford faced in heat. Viewing the phenomena presented by standing waves, it is, to quote Rumford's words, "extremely difficult, if not impossible" to retain the idea of light as consisting of discrete photons. I do not minimize the difficulty of arriving at an explanation of all optical phenomena, such for instance as the Compton effect, exclusively in terms of wave transmission and quantum "vestibules"; nevertheless, on the basis of a long preoccupation with standing waves, I venture to predict that this will be done, and that the photon will go the way of the "caloric" that Rumford demolished.